

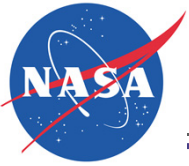
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# Frequency Domain Beamforming for a Deep Space Network Downlink Array

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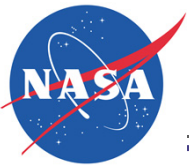
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# Introduction

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- The Deep Space Communication Complex Downlink Array
- Time and Frequency Domain Beamforming
- Analyzer and Synthesizer Filterbanks
- Delay and Phase Corrections
- Array Calibrations
- Sub-Channels
- Conclusions

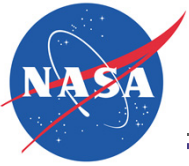


## The Deep Space Communication Complex Downlink Array (DDA)

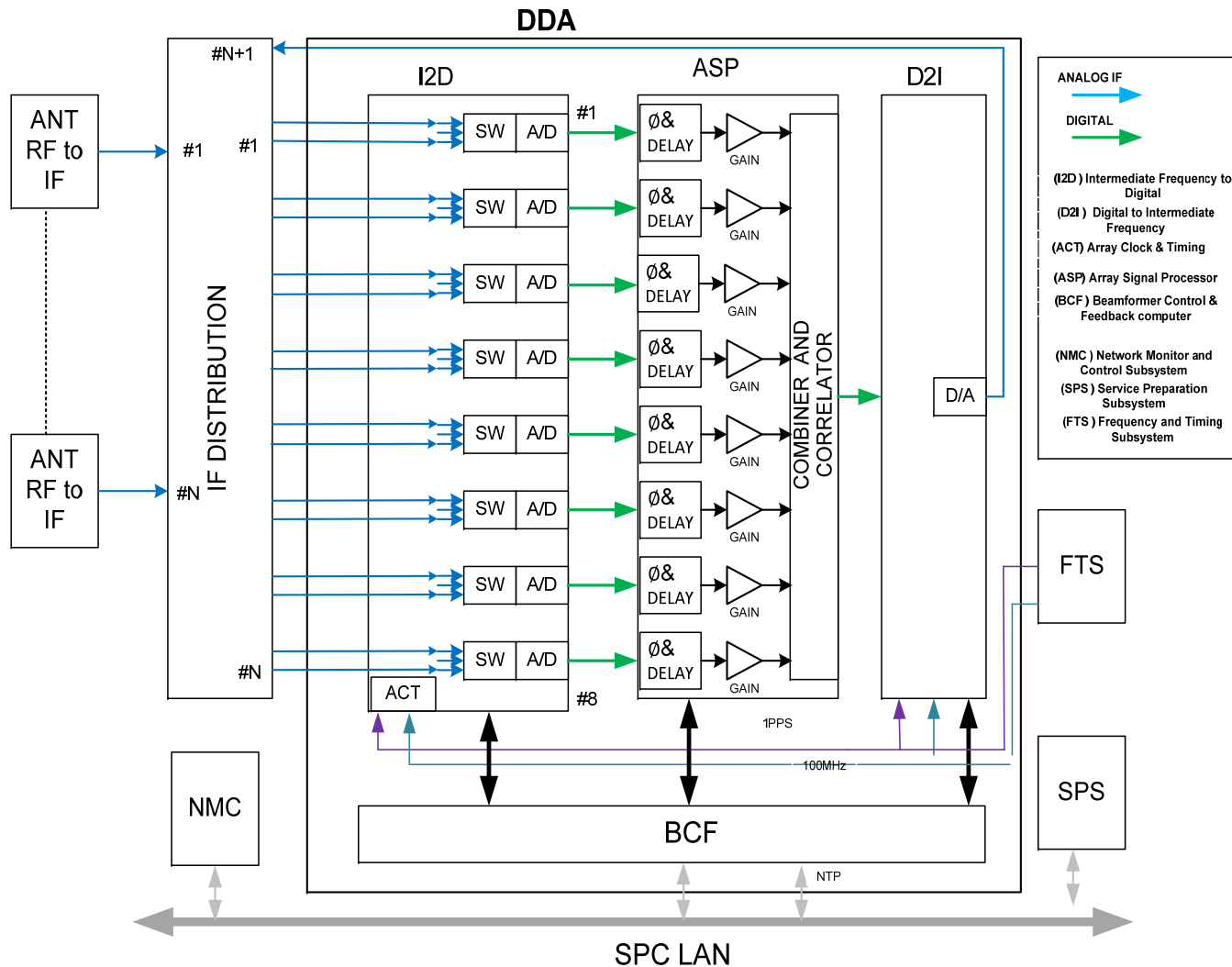
- Three DSN stations (Goldstone, CA; Madrid, Spain; Canberra, Australia)
  - Each has one 70m and multiple 34m antennas. More 34m antennas currently being built. Plan is four 34m antennas at each station.
- DDA to be used to augment and replace 70m antennas with multiple 34m antennas
- The DDA will coherently combine up to 8 inputs at an IF band from 100 to 600 MHz.
- Inputs will be either X band (8.4 GHz) or Ka-Band (32 GHz)
- Antennas used for spacecraft navigation, tracking, telemetry



Canberra 70-meter antenna

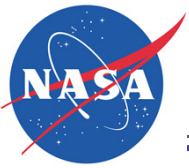


# DSCC Downlink Array



## High Level Functional View of DDA -

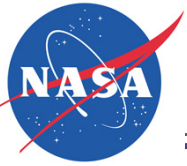
- I2D
  - Analog to Digital Conversion
- ASP
  - Delay and Phase Correction
  - Apply Gain & Combine Antenna
  - Correlate Each Antenna Pair & Send to BCF for feedback.
- D2I
  - Digital to Analog Conversion
- BCF
  - Monitor & Control Computer
  - Uses cross-correlations to calculate delay and phase corrections.



## Time and Frequency Domain Beamforming

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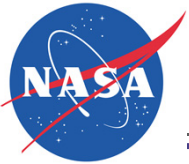
- In order to array DSN antennas in real time
  - Track changing delay due to Earth's rotation
  - Antennas are far enough apart, that Earth rotation causes Doppler shift between antennas.
  - Troposphere causes random path delay fluctuations seen as phase and delay differences across antennas.
- Need to handle telemetry bandwidths from 500 MHz down to 1 KHz.
- Data sampled at 1280 MHz, 8-bits.
  - In order to limit phase errors across the entire 100-600 MHz band, fractional clock delay corrections necessary
- High data rates necessitate processing the data among multiple Field Programmable Gate Arrays (FPGAs) for combining.
  - Data rate per antenna is ~10 Gbits/second.



## Time and Frequency Domain Beamforming

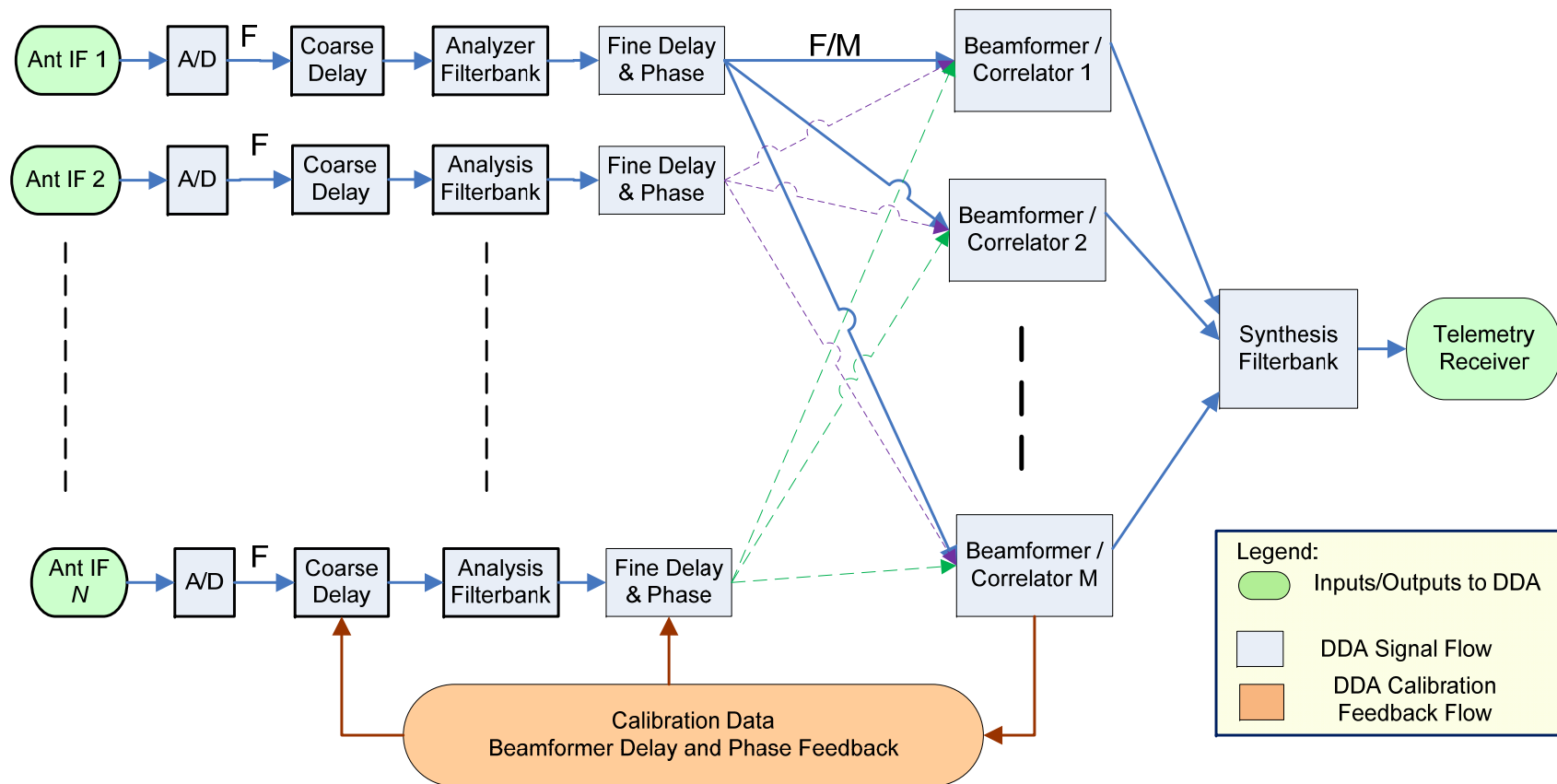
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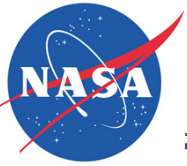
- Time Domain Beamforming
  - Phase & Delay corrections applied to full sampling bandwidth
  - Delays to sample clock resolution performed by large digital delay lines
  - Fractional clock delays implemented using Finite Impulse Response Filters.
    - FIR filters cannot be implemented at 1280 MHz rate in FPGA. Must use parallel logic and lower clock rates (~200 MHz).
  - Difficult to break data up among multiple FPGAs
  - Correlations, for array calibration, require additional off line data path.
- Frequency Domain Beamforming
  - Input signals broken up to smaller frequency channels.
  - Coarse delays still done with large digital delay lines
  - Fractional clock delay implemented as phase shift across frequency channels.
  - Processing can be easily partitioned by frequency across multiple FPGAs.
  - Correlations, for array calibrations, can be performed inline with data.



# Time and Frequency Domain Beamforming

## Frequency Domain Beamforming Data Flow for the DDA

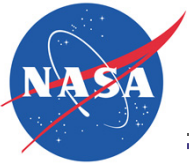




## Analyzer and Synthesizer Filterbanks

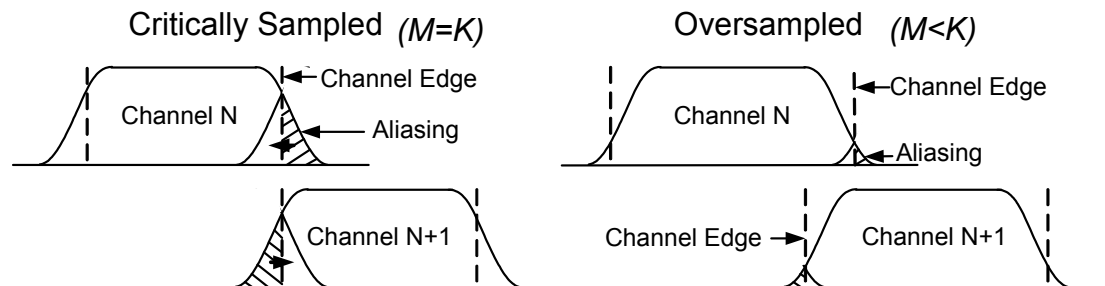
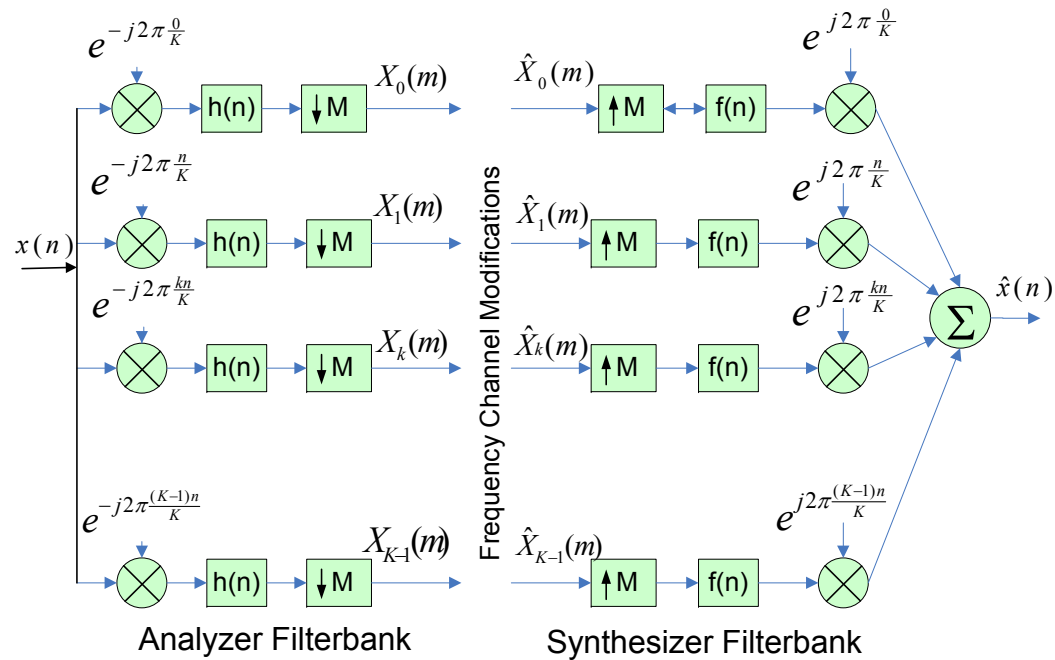
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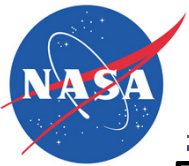
- To process antenna signals as multiple contiguous frequency channels, an Analyzer-Synthesizer filterbank is used.
- Analyzer-Synthesizer Filterbank used based on Discrete Fourier Transform type Filterbanks.
- The filterbank has  $K$  channels, and each channel experiences a downconversion factor of  $M$ .
  - For critically sampled filterbanks,  $M=K$ .
  - For the DDA, the channels are oversampled:  $K/M = 1.25$ .
- Oversampled channels allow near-perfect reconstruction at the output of the Synthesizer filterbank.
  - phase rate corrections for geometric delay may be made in channel specific phase rotators without distortion to reconstructed signal



# Analyzer and Synthesizer Filterbanks

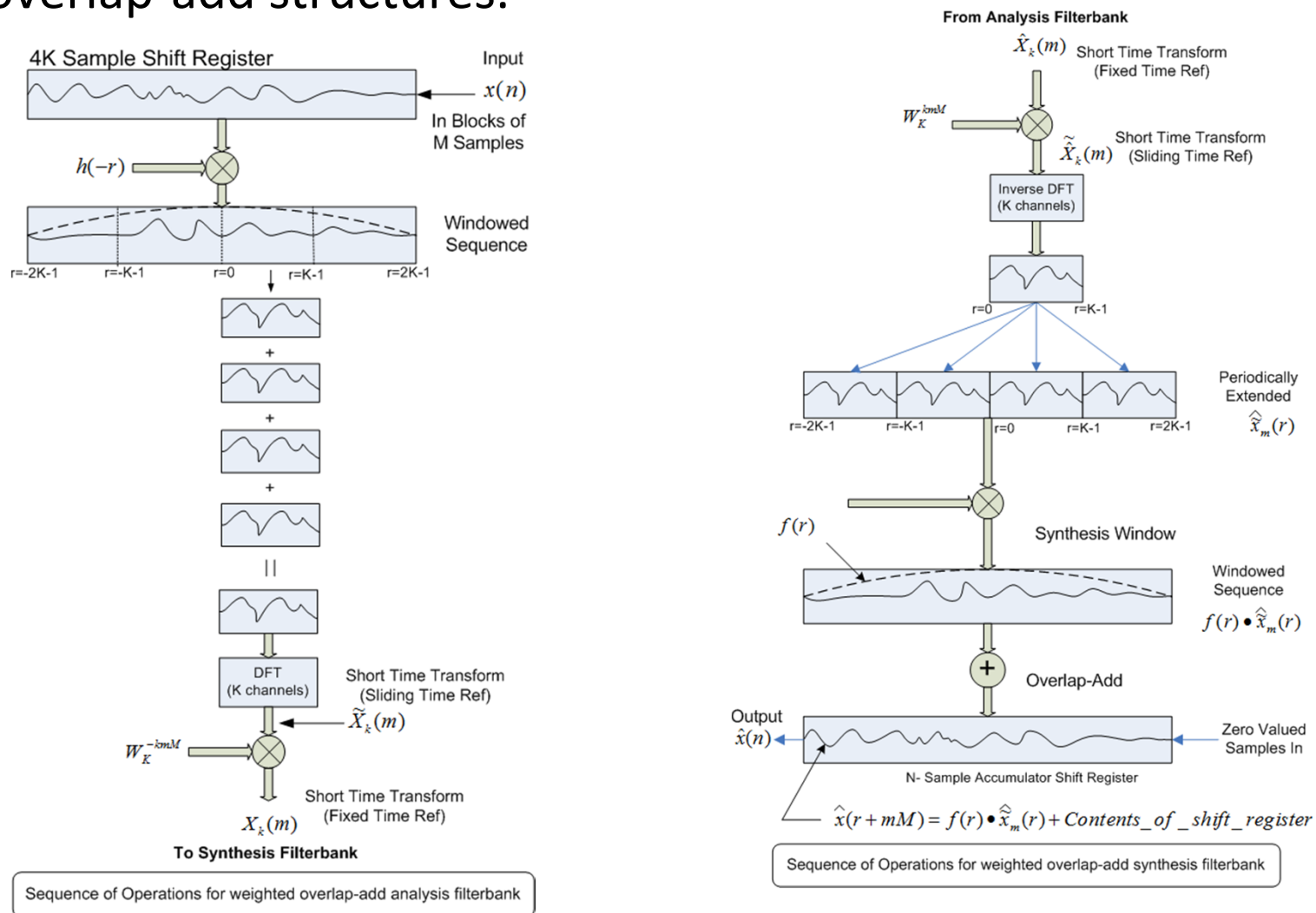
## Discrete Fourier Transform Filterbank Pair

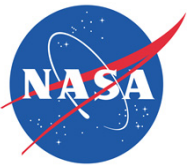




# Analyzer and Synthesizer Filterbanks

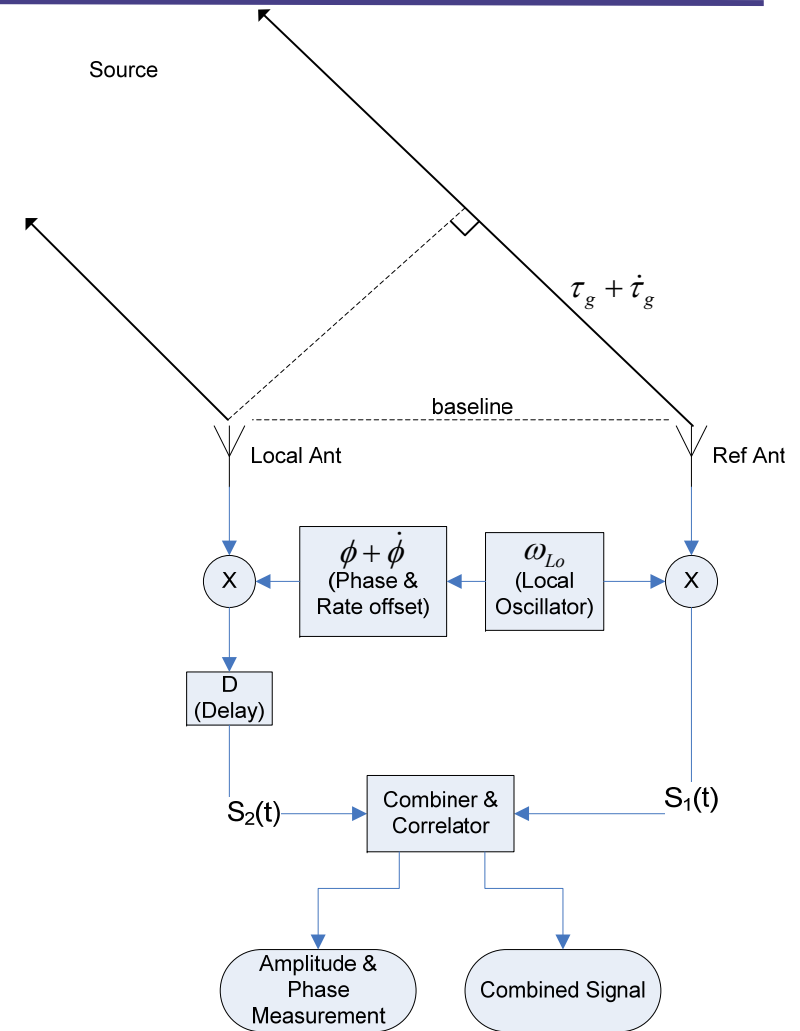
- Filterbanks implemented efficiently using FFT based weighted overlap-add structures.



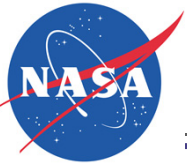


## DSCC Downlink Array Delay Model

- The delay between antennas in a deep space antenna array has three components: Geometric, Instrumental and Tropospheric
- The Geometric Delay is predicable and can be modeled.
- The instrumental delay can be calibrated out through correlation measurements on radio sources.
- The tropospheric delay is random and requires a feedback loop to track.
- The Geometric Delay between each local antenna and a reference position on the ground can be modeled by the figure at right.
- The geometric delay has a delay & delay rate component to model the change in delay from a reference as the Earth rotates.
- In Frequency Domain Beamformer, this delay model applied individually to each frequency channel

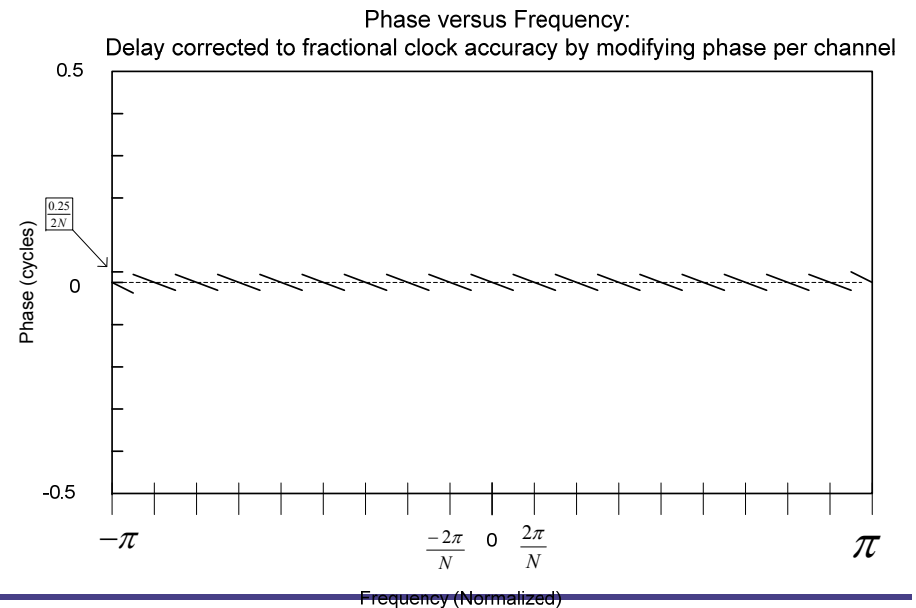
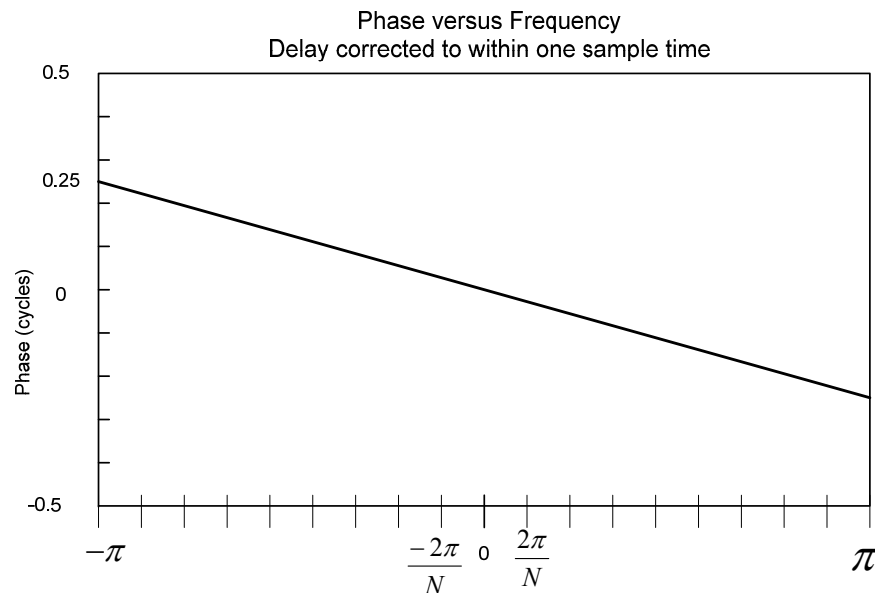


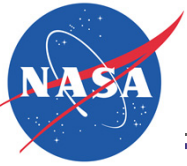
Simplified Model of phase and delay corrections for correlation and combining



## Delay and Phase Corrections

- The Delay model yields a fractional delay term expressed as a phase offset for a given frequency channel:  $-\omega_{RF}(\tau_g - D)$ 
  - The phase offset is given by the RF frequency of the channel times the difference between the geometric delay and the delay quantized to the sample clock (D).
  - Fractional Delay correction done by applying this corrective term to each channel.
- Model also gives a frequency offset term,  $\omega_{rf}\dot{\tau}$ 
  - $\omega_{rf}$  is the RF frequency of a given channel, and  $\dot{\tau}$  is the geometric delay rate of each antenna to the reference.

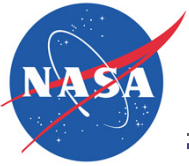




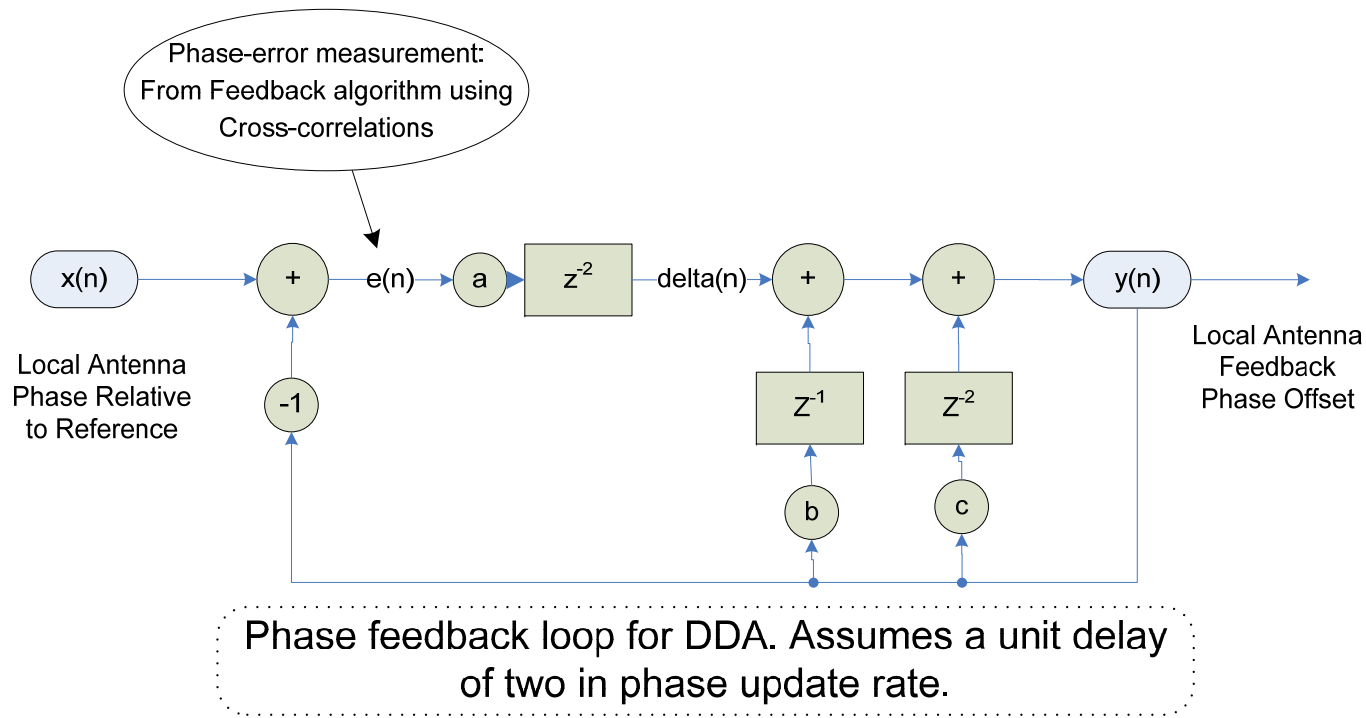
## Array Calibration

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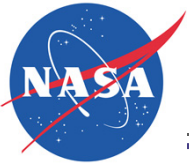
- Calibration performed using a feedback loop tracking array phase and delay versus a reference.
- Phase and delay measurements obtained from cross-correlations of the individual channels of the frequency domain beamformer.
  - Delay estimates obtained from phase slope across channels.
- The amount of cross-correlations are  $\text{Order}(N^2)$ .
- The DDA can use different algorithms to take the correlation matrix and output delay/phase offset measurements.
- The frequency domain beamforming architecture allows the correlators and combiners (per channel) to share the same data stream.
  - Allows considerable savings of high data rate interconnections.



# Array Calibration

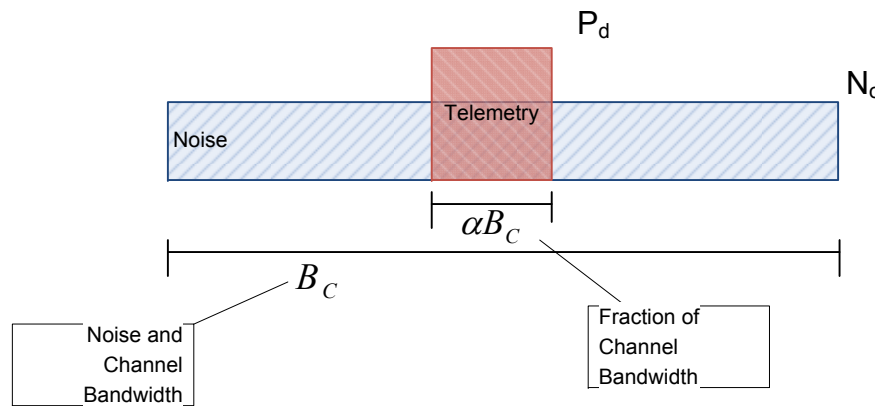


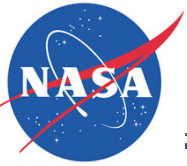
- Phase offset applied across all channels in Frequency Domain Beamformer.
- Delay has similar loop. Delays larger than 1 sample clock applied in coarse delay line, fractional delays applied as delay slope across channels.



## Sub-Channels

- Frequency channels in the DDA are 1.25 MHz in bandwidth.
- Low rate telemetry will all be contained in one or two channels.
- Maximum correlation signal to noise ratio obtained when telemetry is greater than or equal to a frequency channel band.

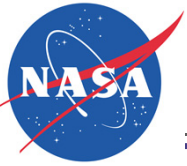




## Sub-Channels

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- DDA adds flexible sub-channels to handle lower telemetry rates.
  - Bandwidth of channels adjustable from 100 KHz down to 125 Hz.
  - Placement of sub-channels flexible among available frequency channels. Each sub-channel can be in a different channel or some can share a common channel.
- Sub-channels are not in-line with data. Used for correlations only.



## Conclusions

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- New antenna array for Deep Space Network designed and currently being implemented
- Coherently combines up to 8 inputs at an IF band from 100 to 600 MHz.
- Frequency Domain Beamforming Architecture
  - This architecture gives flexibility to handle multiple antennas at very high data rates.
  - It allows fractional clock delays to be handled in the frequency domain as a phase shift.
  - The channelized antenna data can be handled in-line for both combining and correlation, prior to re-synthesis to the time domain.
- Array supports telemetry bandwidths from 500 MHz down to 1 KHz using channels and sub-channels.